Neutron-fed afterglows of gamma-ray bursts

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ABSTRACT

A neutron component is practically inevitable in baryonic fireballs of gamma-ray bursts (GRBs). At late stages of the explosion, the neutrons fully decouple from the ion ejecta and coast freely. The presence of the neutron ejecta qualitatively changes the mechanism of the GRB afterglow. The neutrons *lead* the decelerating blast wave and gradually decay, leaving behind a trail of the decay products mixed with the ambient medium. The kinetic energy of the decay products far exceeds the medium rest energy, and the trail has a Lorentz factor $\gamma \gg 1$ at radii up to 10^{17} cm. The ion ejecta decelerate behind as they sweep up the neutron trail and drive a shock wave into it. The afterglow is emitted by the preshock and postshock parts of the neutron trail. The neutron-fed afterglow can re-brighten at an observed time of tens of days.

Subject headings: Cosmology: miscellaneous — gamma-rays: bursts — radiation mechanisms: nonthermal — shock waves

1. Introduction

An important development in the physics of gamma-ray bursts (GRBs) is the recent realization that their fireballs should have a significant neutron component (Derishev, Kocharovsky, & Kocharovsky 1999a,b; Bahcall & Mészáros 2000; Mészáros & Rees 2000; Fuller, Pruet, & Abazajian 2000). In an accompanying paper (Beloborodov 2002), we study in detail the nuclear composition of the baryonic fireballs and show that the presence of neutrons is practically inevitable. One consequence is an observable multi-GeV neutrino emission from inelastic neutron-ion collisions in the ejecta. Here, we focus on a different aspect of the problem. We show that the presence of neutrons has a dramatic impact on the explosion dynamics and propose a novel mechanism for the GRB afterglow emission.

Let us remind what happens in a standard explosion without neutrons (see Mészáros 2002 for a review). The GRB ejecta with mass $M_{\rm ej}$ and Lorentz factor $\Gamma_{\rm ej}$ sweep up the ambient medium and gradually dissipate their kinetic energy. The dissipation rate peaks at a characteristic "deceleration" radius $R_{\rm dec}$ where half of the initial energy is dissipated. This radius corresponds to the swept-up mass $m_{\rm dec} = M_{\rm ej}/\Gamma_{\rm ej}$. Further dynamics is described by the self-similar blast wave model of Blandford & McKee (1976). How does this picture change in the presence of neutrons?

The neutrons develop Lorentz factor $\Gamma_n \sim 300$ at the very beginning of the explosion when the fireball is accelerated by radiation pressure (Derishev et al. 1999b). They are well coupled to the ions in the early dense fireball due to frequent n-i collisions, and decouple close to the end of the acceleration stage. Then the neutrons coast and gradually decay with a mean lifetime in their rest frame $\tau_\beta \approx 900$ s. The mean radius of decay is $R_\beta = c\tau_\beta\Gamma_n$, and the main parameter that controls the impact of neutrons on the blast wave is

$$H = \frac{R_\beta}{R_{\rm dec}}, \qquad R_\beta = 0.9 \times 10^{16} \left(\frac{\Gamma_n}{300}\right) \text{ cm}. \tag{1}$$

In the limit of $H \to 0$, no neutrons would survive till the afterglow. Pruet & Dalal (2002) studied this case recently. In this Letter, we show that $H > 0.1$ implies a qualitative change in the blast wave mechanism. A plausible value of H is above unity and definitely above 0.1. Indeed, an upper bound on $R_{\rm dec}$ can be inferred from observations: (1) BeppoSax reveals the X-ray afterglow immediately after the main GRB (Frontera et al. 2000). Hence, the ejecta deceleration begins at an observer time $(1+z)(R_{\rm dec}/2\Gamma_{\rm ej}^2 c) < 10$ s, which implies $R_{\rm dec} < 2 \times 10^{16}(\Gamma_{\rm ej}/300)^2$ cm for a typical redshift $z \sim 2$. (2) The radius of the blast wave after its deceleration was estimated from the radio scintillation pattern of the late afterglow. $R \approx 10^{17}$ cm was found at $t = 4$ weeks for GRB 970508 (Frail et al. 1997). A similar analysis gives $R \lesssim 10^{17}$ cm at

$t = 10 - 40$ days in GRB 980703 (Berger, private communication). Thus, an almost complete deceleration occurs within 10^{17} cm, and it should have begun at $R_{\rm dec} < 10^{16}$ cm. This implies $H > 1$.

An outline of the neutron-fed explosion is as follows. At radii under consideration, $R > 10^{15}$ cm, the n- and i- components of the GRB ejecta can be viewed as two decoupled thin shells (the ejecta thickness is $\Delta = ct_b \ll R$, where $t_b = 0.1 - 100$ s is the burst duration). The n-shell coasts with a constant Γ_n and *leads the decelerating blast wave*. It gradually decays and leaves behind a trail of decay products mixed with the ambient medium. The trail is formed *relativistically hot and moving with a high Lorentz factor* $1 \ll \gamma < \Gamma_n$. The i-shell follows with a Lorentz factor Γ ($\gamma < \Gamma < \Gamma_n$) and drives a shock wave into the trail. Surprisingly, this picture holds up to $10R_\beta \approx 10^{17}$ cm and covers the major stage of the afterglow.

2. Neutron front and its trail

As the ion ejecta component decelerates, it falls behind and separates from the neutrons. Thus, the ejected neutrons and ions form two distinct shells, which we call the n- and i- shells. The i-shell lags behind by a distance l,

$$\frac{l}{R} \approx \beta_n - \beta_i = \frac{1}{2\Gamma^2} - \frac{1}{2\Gamma_n^2}, \tag{2}$$

where β_i and β_n are the shell velocities in units of c, and Γ and Γ_n are their Lorentz factors. The shells are completely separated when l exceeds their thickness Δ. This happens when Γ falls below $\Gamma_{\rm sep}$ defined by $l = \Delta$. For example, with $R_{\rm dec} = 10^{16}$ cm, $\Delta/c = 1$ s, and $\Gamma_n = 300$, we get $\Gamma_{\rm sep} = 0.8\Gamma_n$. For simplicity, we hereafter consider the stage $\Gamma < \Gamma_{\rm sep}$. It covers the whole explosion if $\Delta \to 0$.

The mass of the n-shell gradually decreases because of the β-decay,

$$M_n(R) = M_n^0 \exp\left(-\frac{R}{R_\beta}\right). \tag{3}$$

The decay products p and e^- share immediately their momentum with ambient particles due to the two-stream instability (the timescale of the plasma processes is set by the ion plasma frequency ω_i, and it is the shortest timescale in the problem). Thus, the n-shell leaves behind a mixture of the ambient particles with the decay products, and this trail has a well defined bulk velocity $\beta = v/c$, which we calculate now.

Let $\mathrm{d}m = (\mathrm{d}m/\mathrm{d}R)\mathrm{d}R$ be the ambient mass overtaken by the neutron front as it passes $\mathrm{d}R$ and $\mathrm{d}M_n = (M_n/R_\beta)\mathrm{d}R$ be the mass of decayed neutrons. The $\mathrm{d}m$ and $\mathrm{d}M_n$ share momentum and form a trail element with proper mass $\mathrm{d}m_* = \mathrm{d}M_n + \mathrm{d}m + \mathrm{d}m_{\rm heat}$, which includes heat dissipated in the inelastic

$\mathrm{d}m - \mathrm{d}M_n$ collision. The laws of energy and momentum conservation read

$$\Gamma_n \mathrm{d}M_n + \mathrm{d}m = \gamma \mathrm{d}m_*, \qquad \beta_n \Gamma_n \mathrm{d}M_n = \beta\gamma \mathrm{d}m_*, \tag{4}$$

where $\gamma = (1-\beta^2)^{-1/2}$ is the trail Lorentz factor. Let us denote

$$\zeta(R) = \frac{\mathrm{d}M_n}{\mathrm{d}m} = \frac{M_n}{R_\beta}\left(\frac{\mathrm{d}m}{\mathrm{d}R}\right)^{-1}. \tag{5}$$

From equations (4) we find

$$\beta(R) = \frac{\beta_n}{1+(\Gamma_n\zeta)^{-1}}, \qquad \gamma(R) = \frac{\Gamma_n\zeta + 1}{(\zeta^2 + 2\Gamma_n\zeta + 1)^{1/2}}. \tag{6}$$

It gives $\gamma \gg 1$ until essentially all neutrons have decayed. To illustrate this important point let us specialize to a power-law density profile of the ambient medium. Then

$$m(R) = m_\beta \left(\frac{R}{R_\beta}\right)^k, \qquad \zeta(R) = \frac{M_n}{k m_\beta}\left(\frac{R}{R_\beta}\right)^{1-k}, \tag{7}$$

where m_β is the ambient mass inside R_β. At $R = R_\beta$ we have $\zeta = (M_n^0 e^{-1}/k m_\beta) \gg 1$, and at $R > R_\beta$, ζ decreases exponentially as M_n decays according to equation (3). One can define a characteristic radius R_{trail} where γ drops to unity. This happens when $\zeta \approx \Gamma_n^{-1}$, after ≈ 10 e-foldings of the decay (for typical $m_\beta \sim m_{\mathrm{dec}} \sim 10^{-5} M_n^0$). Thus,

$$R_{\mathrm{trail}} \approx 10 R_\beta \approx 10^{17}\left(\frac{\Gamma_n}{300}\right) \text{ cm}. \tag{8}$$

Note that R_{trail} weakly depends on the initial neutron fraction $X_n = M_n^0/M_{\mathrm{ej}}$ as long as $X_n \gg \Gamma_n^{-2}$. R_{trail} has almost equal values for $X_n = 0.9$ and $X_n = 0.01$.

We now calculate the trail density. The n-shell is thin and the ambient particles cross it almost instantaneously (on timescale $\gamma^2\Delta/c \ll R/c$). Measured in the n-shell frame, the flux of ambient particles is

$$\beta_n \Gamma_n n_0 = (\beta_n - \beta)\Gamma_n \gamma n_{\mathrm{amb}}. \tag{9}$$

Here n_0 and n_{amb} are the proper densities of the ambient particles ahead and behind the front, respectively. The total density of the trail, n, includes the neutron decay products: $n = (1+\zeta) n_{\mathrm{amb}}$. We find (using eq. 6),

$$\frac{n}{n_0} = \frac{\beta_n(1+\zeta)}{\gamma(\beta_n - \beta)} = (1+\zeta)\left(\zeta^2 + 2\Gamma_n\zeta + 1\right)^{1/2}. \tag{10}$$

When $\zeta < 1$, the density of the decay products is small, $n \approx n_{\mathrm{amb}}$, and the density enhancement is solely due to compression of the ambient medium accelerated in the neutron front. The compression factor is n_{amb}/n_0 is found from equation (9).

The energy dissipated in the neutron front is given by

$$\mathrm{d}E_{\mathrm{n.f.}} = \gamma\,(\mathrm{d}m_* - \mathrm{d}m - \mathrm{d}M_n)\,c^2 = (\Gamma_n - \gamma)\,\mathrm{d}M_n c^2 - (\gamma - 1)\mathrm{d}m\,c^2. \tag{11}$$

After simple algebra (using eqs. 4), we find

$$\frac{\mathrm{d}E_{\mathrm{n.f.}}}{\mathrm{d}R} = \left[\frac{\Gamma_n\beta_n - \gamma\beta}{\Gamma_n\gamma(\beta_n - \beta)} - 1\right]\gamma\frac{\mathrm{d}m}{\mathrm{d}R}\,c^2. \tag{12}$$

It simplifies to $\mathrm{d}E_{\mathrm{n.f.}} = 2\gamma^2\mathrm{d}mc^2$ for the interesting regime $1 \ll \gamma \ll \Gamma_n$ ($\Gamma_n^{-1} < \zeta < \Gamma_n$). The trail is formed very hot. This can be seen when comparing inertial mass $\mathrm{d}m_*$ (that includes heat) with rest mass $\mathrm{d}M_b = \mathrm{d}m + \mathrm{d}M_n = (1+\zeta)\mathrm{d}m$, which gives the dimensionless relativistic enthalpy of the trail (we use eqs. 4 and 5),

$$\mu = \frac{\mathrm{d}m_*}{\mathrm{d}M_b} = \frac{(\zeta^2 + 2\Gamma_n\zeta + 1)^{1/2}}{1+\zeta}. \tag{13}$$

We find $\mu \gg 1$ for $\Gamma_n^{-1} < \zeta < \Gamma_n$, i.e. the internal energy of the trail far exceeds its rest energy. The trail parameters for different ζ are summarized in Table 1.

It is instructive to view the dissipation process in the rest frame of the trail. Here, the elements $\mathrm{d}m$ and $\mathrm{d}M_n$ have initial Lorentz factors γ and $\tilde{\gamma} = \Gamma_n\gamma(1 - \beta\beta_n)$, share their opposite momenta, and come at rest. This is achieved via the plasma instability that isotropizes the particle momentum distribution. It may result in two isotropic distributions: the ambient ions with mean Lorentz factor γ and the decay-product protons with mean Lorentz factor $\tilde{\gamma}$. Thus the trail can consist of two ion populations with different temperatures. Both populations are relativistically hot, $\gamma \gg 1$ and $\tilde{\gamma} \gg 1$, if $\Gamma_n^{-1} < \zeta < \Gamma_n$. They have equal internal energies $(\tilde{\gamma} - 1)\mathrm{d}M_n \approx (\gamma - 1)\mathrm{d}m$ (which correspond to their equal relativistic bulk momenta before coming at rest in the trail frame), and hence the ratio of their temperatures is the reciprocal of their density ratio.

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Table 1: Trail parameters

	$\zeta > \Gamma_n$	$1 < \zeta < \Gamma_n$	$\Gamma_n^{-1} < \zeta < 1$	$\zeta < \Gamma_n^{-1}$
γ	Γ_n	$(\Gamma_n\zeta/2)^{1/2}$	$(\Gamma_n\zeta/2)^{1/2}$	1
n/n_0	ζ^2	$2\gamma\zeta$	2γ	1
μ	1	$\Gamma_n/\gamma \approx 2\tilde{\gamma}$	2γ	1

A detailed model of the dissipation in the n-shell is an interesting plasma physics problem, which we defer to a future work. We emphasize here that it is different from dissipation in collisionless shocks. The thickness of a standard shock, $\delta \sim 10c/\omega_i$, is set by the instability timescale, and it is a discontinuity in the hydrodynamical sense. By contrast, the n-shell has thickness $\Delta \sim 10^{11} - 10^{12}$ cm, which is 5-7 orders of magnitude larger than δ. The neutrons decay and cause dissipation everywhere in the n-shell. The medium velocity grows smoothly from 0 at the leading edge to β at the trailing edge of the n-shell. The dissipation here can be called "volume dissipation".

3. Shock wave

The i-shell follows the n-shell and collects its trail. As a result (1) the Lorentz factor of the i-shell, Γ, decreases, and (2) a shock wave propagates into the trail material. The shock front is between the i- and n-shells; it has a Lorentz factor $\Gamma \lesssim \Gamma_{\rm sh} < \Gamma_n$ and cannot catch up with the neutron front[4]. Given the shell separation l (eq. 2) we find the time it takes the i-shell to pick up the trail,

$$t_i = \frac{l}{c(\beta_i - \beta)} \approx \frac{\gamma^2}{(\Gamma^2 - \gamma^2)} \frac{R}{c}. \tag{14}$$

It is much shorter than R/c as long as $\Gamma \gg \gamma$. Hereafter we use the approximation $t_i < R/c$ and assume that the trail is picked up before it could expand and change its density or velocity. We allow, however, for rapid radiative losses because the trail may cool on a timescale $t_{\rm cool} \ll R/c$ and possibly $t_{\rm cool} < t_i$. Below we considers two extreme cases: $t_{\rm cool} \gg t_i$ ("adiabatic" trail) and $t_{\rm cool} \ll t_i$ ("radiative" trail with $\mu = 1$).

In the radiative regime, the energy dissipated by the shock is

$$\frac{{\rm d}E_{\rm sh}}{{\rm d}R} = \Gamma(\Gamma_{\rm rel} - 1)(1+\zeta)\frac{{\rm d}m}{{\rm d}R}\, c^2, \tag{15}$$

where $\Gamma_{\rm rel} = \Gamma\gamma(1 - \beta_i\beta)$ is the trail Lorentz factor with respect to the i-shell. For $\Gamma_n^{-1} \ll \zeta \ll \Gamma_n$ $(1 \ll \gamma \ll \Gamma_n)$ one can use the approximate expressions $\zeta = 2\gamma^2/\Gamma_n$ and $\Gamma_{\rm rel} = (1/2)(\gamma/\Gamma + \Gamma/\gamma)$ to get

$$\frac{{\rm d}E_{\rm sh}}{{\rm d}R} = \left(\frac{1}{2\gamma} + \frac{\gamma}{\Gamma_n}\right)(\Gamma - \gamma)^2\, \frac{{\rm d}m}{{\rm d}R}\, c^2. \tag{16}$$

Note that the dissipation is smaller than it would be in the absence of the neutron front, ${\rm d}E_{\rm sh} = \Gamma(\Gamma - 1){\rm d}mc^2$. Hence, in the radiative regime, the neutrons delay the i-shell deceleration.

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[4]We do not consider here steep ambient density profiles, $n_0(R)$. If n_0 falls off steeper than R^{-3} the shock front accelerates rather than decelerates (Shapiro 1980) and may overtake the n-shell.

In the adiabatic regime, the preshock material has enthalpy μ given by equation (13). The postshock heat, measured in the lab frame, is $\mathrm{d}E_{\mathrm{heat}} = \Gamma(\Gamma_{\mathrm{rel}}\mu - 1)(1+\zeta)\mathrm{d}m$. It includes heat deposited by the neutron front, which should be subtracted to get the energy dissipated in the shock itself. Hence,

$$\frac{\mathrm{d}E_{\mathrm{sh}}}{\mathrm{d}R} = \left[\Gamma(\Gamma_{\mathrm{rel}}\mu - 1) - \gamma(\mu - 1)\right](1+\zeta)\frac{\mathrm{d}m}{\mathrm{d}R}\,c^2. \tag{17}$$

For $1 \ll \gamma < \Gamma_n$ we get $\mathrm{d}E_{\mathrm{n.f.}} = 2\gamma^2\mathrm{d}mc^2$, $\mathrm{d}E_{\mathrm{sh}} = (\Gamma^2 - \gamma^2)\mathrm{d}mc^2$, and the total dissipated energy $\mathrm{d}E_{\mathrm{heat}} = (\Gamma^2 + \gamma^2)\mathrm{d}mc^2$. As long as $\Gamma \gg \gamma$, the bulk of energy is dissipated in the shock rather than in the neutron front. Moreover, the dissipated energy is the same as in the absence of the neutron front, and hence the i-shell deceleration is the same.

In both radiative and adiabatic regimes, the shock dissipation is suppressed when the blast wave decelerates to $\Gamma \sim \gamma$. At $\Gamma = \gamma$ the shock would disappear completely. Thus, Γ is bound from below by γ.

4. Example model

Let us consider the radiative regime. The mass of the i-shell grows, $M(R) = M_{\mathrm{ej}} + m - M_n$, as it picks up the trail material. Mass gain $\mathrm{d}M$ causes deceleration $\mathrm{d}\Gamma$ that is found from the energy and momentum conservation: $\mathrm{d}(\Gamma M) = \gamma\mathrm{d}M - \mathrm{d}E_{\mathrm{rad}}/c^2$ and $\mathrm{d}(\beta_i\Gamma M) = \beta\gamma\mathrm{d}M - (\mathrm{d}E_{\mathrm{rad}}/c^2)\beta_i$, where $\mathrm{d}E_{\mathrm{rad}} = \mathrm{d}E_{\mathrm{sh}}$ is the radiated energy. Excluding $\mathrm{d}E_{\mathrm{rad}}$, we get the dynamic equation for the i-shell,

$$M\frac{\mathrm{d}\Gamma}{\mathrm{d}R} = -\Gamma^2\gamma\beta_i(\beta_i - \beta)(1+\zeta)\frac{\mathrm{d}m}{\mathrm{d}R}. \tag{18}$$

It can be solved for $\Gamma(R)$ with an initial condition Γ_{ej}. An example solution for a wind-type medium ($k=1$) is shown in Figure 1; for a constant-density medium, $k=3$, the results are similar. With $k=1$ we have $\zeta = M_n/R_\beta$, and

$$\gamma(R) \approx \gamma_0 \exp\left(-\frac{R}{2R_\beta}\right), \qquad \gamma_0 = \left(\frac{\Gamma_n M_n^0}{2m_\beta}\right)^{1/2} = \Gamma_n\left(\frac{X_n}{2H}\right)^{1/2}. \tag{19}$$

The transition to $\gamma \approx 1$ occurs at $R_{\mathrm{trail}} \approx \log(2\gamma_0^2)$. In our numerical example, $H = \Gamma_{\mathrm{ej}}m_\beta/M_{\mathrm{ej}} = 10$, $X_n = 0.5$, and $\Gamma_n = \Gamma_{\mathrm{ej}} = 300$, which gives $\gamma_0 = 47$ and $R_{\mathrm{trail}} = 8.4R_\beta$. The medium acceleration to $\gamma \gg 1$ delays the deceleration of the i-shell, especially when Γ approaches γ (Fig. 1).

The explosion has two separate emission regions: behind the neutron front and behind the shock front. They have different luminosities and spectra. In the radiative model, the luminosities equal the corresponding dissipation rates ($c\,\mathrm{d}E_{\mathrm{n.f.}}/\mathrm{d}R$) and ($c\,\mathrm{d}E_{\mathrm{sh}}/\mathrm{d}R$) (Fig. 1). The neutron front dissipation

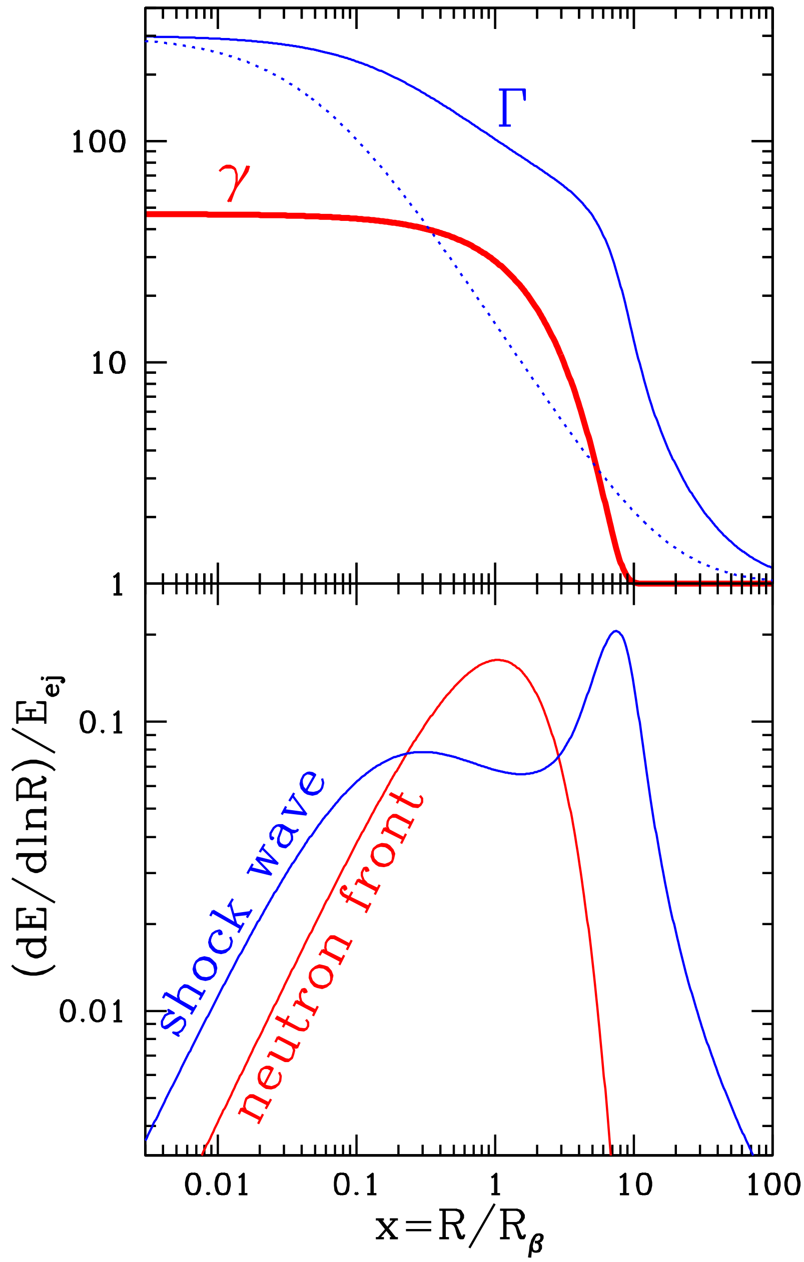

Fig. 1.— Example radiative model with $k = 1$, $H = 10$, $X_n = 0.5$, and $\Gamma_n = \Gamma_{\rm ej} = 300$. *Top:* Trail Lorentz factor γ and the i-shell Lorentz factor Γ. The dotted curve shows the i-shell deceleration $\Gamma(R)$ that would take place without neutrons. *Bottom:* Radial distribution of the dissipation rate in the neutron front and the shock front. $E_{\rm ej} = \Gamma_{\rm ej} M_{\rm ej} c^2$ is the initial total energy of the ejecta. Radius R is measured in units of the mean decay radius R_β (eq. 1).

peaks at R_β, and the shock dissipation has two peaks. The first peak marks the beginning of the i-shell deceleration, and it is followed by a minimum when Γ approaches γ. At $R > 2R_\beta$, γ falls down steeply, and the second peak is reached at $R \approx R_{\rm trail}$ where $\gamma \sim 1$; it compensates for the preceding delay of the i-shell deceleration.

5. Discussion

The details of the emission mechanism in a neutron-fed explosion remain to be investigated. Magnetic field is an important ingredient, for the observed emission is believed to be synchrotron. The ambient field is weak, and standard models without neutrons rely on a mechanism of field generation in the shock. Indeed, the two-stream instability, which maintains the collisionless shock, generates a strong turbulent field, comparable to the equipartition value, (Sagdeev 1966, Medvedev & Loeb 1999, Gruzinov 2001). The shock front is, however, very thin, and the postshock field decays quickly. A successful model needs a significant remnant field to survive in an extended layer behind the shock, which is uncertain. This problem can be alleviated in a neutron-fed explosion. Here, the leading neutron front is an additional dissipation region maintained in a turbulent state, likely with a strong magnetic field. The shell thickness $\Delta \sim 10^{11} - 10^{12}$ cm is much larger than the thickness of shock fronts, and, even if the field decays immediately behind the n-shell, a significant synchrotron emission may come from the n-shell itself. The magnetic field problem would be resolved if the afterglow data are fitted by a model of a thin $\Delta \sim 10^{-5}R$ magneto-active shell with nearly equipartition magnetic field. A recent work by Rossi & Rees (2002) suggests that this may work.

The observed emission can also come from the shock wave in the neutron trail. We emphasize that this shock is different from the standard one: it propagates in a relativistically moving, dense, and hot medium. The shock dissipation has an interesting bump at $R_{\rm bump} \lesssim R_{\rm trail}$ (Fig. 1). The arrival time of the bump emission is $t_{\rm bump} = (1-\beta_i)R_{\rm bump}/c$. If the i-shell has decelerated by that time, $t_{\rm bump}$ should be a few tens of days. Intriguingly, it coincides with the bumps observed in some afterglows, which were interpreted as supernova accompanying the GRBs (Bloom et al. 1999; Reichart 1999). The neutrons may provide an alternative explanation for the afterglow re-brightening.

If the ejecta is initially beamed within an angle $\theta_{\rm ej}$, the shock dynamics must change when $\Gamma < \theta_{\rm ej}^{-1}$: the ion ejecta tend to spread laterally and their beaming angle grows, $\theta_i > \theta_{\rm ej}$, while the neutron beaming remains constant, $\theta_n = \theta_{\rm ej}$. Then the effective neutron fraction X_n increases at $\theta \leq \theta_{\rm ej}$ (and $X_n = 0$ at $\theta_{\rm ej} < \theta < \theta_i$). The blast density is highest near the ejecta axis where the neutron trail persists, and the observed emission will be sensitive to the observer position with respect to the axis.

We focused here on the neutron front and did not account for the γ-ray precursor that impacts the blast wave dynamics at $R < R_{\rm acc} = 0.7 \times 10^{16}(E_\gamma/10^{53})^{1/2}$ cm, where E_γ is the isotropic energy of the GRB. The analysis in this Letter is strictly valid for afterglows emitted at $R > R_{\rm acc}$. Then the radiation-front effects described in Beloborodov (2002), including the gap opening at $R < 0.3R_{\rm acc}$, occur at smaller radii, and apply to the early afterglow. For a dense medium, where $R_{\rm dec} < R_{\rm acc}$, the effects of the neutron and γ-ray fronts should be studied together.

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